A Workshop in Computational Fluid Dynamics in the Steel Industry

Summary of Presentations and Discussion
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PARTICIPANTS

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Steel Industry	Mark Atkinson	National Steel Corporation
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	Jeffery Ives	The Timken Company
	Bulent Kocatulum	Bethlehem Steel
	Thinium Natarajan	U.S. Steel Group
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	Achilles Vassilicos	U.S. Steel Group
Equipment Manufacturers and Software Suppliers	Paul Debski	Bricmont, Inc.
	Victor Demidovitch	Bricmont, Inc.
	Chokri Guetari	AEA Technology Engineering Software
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Universities	Yun Li	Carnegie Mellon University
	Yogesh Sahai	The Ohio State University
	Brian Thomas	University of Illinois—at Urbana-Champaign
	Chenn Zhou	Purdue University Calumet
National Laboratories	Shen-Lin Chang	Argonne National Laboratory
	Tim McIntyre	Oak Ridge National Laboratory
	Thomas O'Brien	National Energy Technology Laboratory
US Department of Energy	Peter Salmon-Cox	U.S. Department of Energy
Associations/Trade Organizations	Raymond Monroe	Steel Founders' Society
	Joseph Vehec	American Iron and Steel Institute
Other	Carolyn Dimmick	Eichleay Engineers
	Nancy Margolis	Energetics, Inc.
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INTRODUCTION

Dr. Peter Salmon-Cox gave a brief introduction and then introduced Dr. Tyler Thompson from The Dow Chemical Company. Dr. Salmon-Cox is the Acting Steel Team Leader for the Department of Energy's Office of Industrial Technologies.

MULIT-PHASE FLUID DYNAMICS RESEARCH CONSORTIUM

Dr. Tyler Thompson of The Dow Chemical Company (Dow) began the meeting by describing the Multiphase Fluid Dynamics Research Consortium (MFDRC) in the chemical industry. The consortium is "a leveraged collaboration of chemical companies committed to improving [the chemical industry's] ability to model industrial gas-solid transport systems." Dr. Thompson told workshop attendees that building a consortium "doesn't happen in a day." There needs to be a core group to build consensus. He told the participants that they should gather a list of applications important for the steel industry and put together a program rather than a project. Dr. Thompson described the chemical industry's team and the partnership with the Department of Energy's Office of Industrial Technologies. He described how the National Laboratories, universities and chemical industry all worked together. Continuing, he described the needs of the national chemical industry, which includes a computational fluid dynamics (CFD) code that accurately:

- Describes gas-solid hydrodynamics in lean and dense phase flow
- Predicts reactor productivities
- Predicts particle attrition and models cohesion
- Predicts saltation velocities
- Provides scale-up parameters for large scale plants

He noted that the chemical industry requires short development times for riser reactors and fluidized beds and better pneumatic conveying and classifying systems. Dr. Thompson also described various applications and related problems.

He also noted the benefits of the consortium, including direct access to the best researchers, early access to pre-competitive research, and a pool of potential employees. Other benefits include advanced technology for characterizing gas-solid flow (not possible for one company to accomplish) and knowledge building (i.e., close communication with CFD developers, access to data along with the people who developed it, shorten learning curve for company specialists, timely application of advance methods to company problems, and a pool of expertise in the field.)

Dr. Thompson mentioned some of the benefits that have resulted in this cost-shared effort between the Federal Government and chemical industry consortium including:

- Sandia experimental rig
- MFIX reaction kinetics
- New diagnostics
- Advanced computations
- Improved models

Throughout his presentation Dr. Thompson emphasized the importance of team building. Other contributors to success include a shared vision, self-organized team, commitment, leadership by personal initiative, industrial readiness, and tool development.

APPLICATION OF FLUID DYNAMICS IN THE STEEL PRODUCTING INDUSTRY

Following Dr. Thompson were presentations given by representatives from Bethlehem Steel (Bulent Kocatulum), National Steel (Mark Atkinson), The Timken Company (Jeffery Ives) and U.S. Steel (Achilles Vassilicos). Each steel industry representative presentation described the application of CFD in the steel-producing industry. Speakers noted past and current CFD programs, as well as future areas of study, which would be of special interest to the Steel Industry. Examples of past and current CFD modeling efforts that were discussed, and which can be viewed as successful, include, but are not limited to, tundish liquid steel processing to improve steel cleanness in steady state and during ladle transitions, modeling melt flow and heat transfer in the continuous casting mold, argon gas stirring in ladles and in ladle furnaces, RH degassing, melt flow in a submerged entry nozzle (SEN), and slide gate, and other applications. Even in these areas, however, the need for increased precision and validation of predictions obtained with current CDF tools was emphasized. Steel industry representatives noted that future CFD modeling efforts, when combined with other ongoing research efforts to better understand the micro thermo-chemical and metallurgical interactions/transitions of melts, slags, precipitates and gaseous phases (as, for example, at Carnegie Mellon University's Center for Iron and Steel Research), have the potential to enable:

- Better understanding of the complex interactions between various processing steps
- Better scheduling and control of operations
- Deduction in waste of energy, materials, and time
- Improved quality of steel products
- Reduction of cost
- Transient, non-symmetric liquid steel flow in tundish to further improve steel cleanliness

Some important technical areas where CFD is expected to have a significant impact include:

- Alumina plugging in tundish nozzles and flow passages
- Clean steel practices in the continuous casting mold
- Control of slag carryover from ladle and tundish
- Control of superheat during casting
- Vacuum degasser performance and refractory efficiency
- Optimization of thermal and deoxidation operations in ladles
- Melt mixing and oxygen lance performance in basic oxygen furnaces
- Coal injection and hearth performance in blast furnaces

Achilles Vassilicos noted the key requirements for successful CFD, including the following:

- Deep understanding of the mathematics, physics, and methodology
- Reliable software and adequate computing resources
- Means for physical validation
- Highly trained people capable of recognizing strengths and pitfalls

Dr. Vassilicos noted that CFD tools must bring successfully together three components:

- Mathematical representation of the general physics

- Description of the relevant special physics both in macro and sub-grid scales
- Computational capability on mesh scales that resolve the dominant interactions

He also noted that, from a more fundamental standpoint, CFD challenging problems relevant to the steel producing industry include:

- Bulk coupled multi-phase flows, including interactions between gas bubbles and inclusions
- Vortex flows
- Flows in the presence of phase change
- Combustion, including combustion instability
- Free-surface multiphase flows
- Turbulence, including intermittent and re-laminarization regimes

What makes these problems particularly difficult in the case of the steel industry is that they typically occur in the presence of thermo-chemical reactions. It is obvious that the fundamental problems that are relevant to the steel industry community are at the leading edge of challenges facing the CFD and computational science today.

Steel industry representatives concluded that significant background work exists on CFD applications in steel technology. CFD offers the potential for broader impact provided that CFD tools offering higher levels of precision for a range of fundamental phenomena become available. To achieve that, the steel industry has the opportunity to take an active role in:

- Leading an industry-wide effort to develop improved CFD tools
- Tapping into CFD resources at National laboratories and academic institutions
- Defining the areas of fundamental phenomena that underpin steel technology
- Spearheading the development of a library of "standard" problems for CFD model validation for steel
- Identifying and cooperating with other research efforts in steel and chemical industries that have strong synergies with CFD

APPLICATIONS OF CFD IN THE STEEL EQUIPMENT MANUFACTURING INDUSTRY/CFD SOFTWARE SUPPLIERS

Chokri Guetari from AEA Technology Engineering Software discussed issues facing the metal industry and how CFD can help. Some of the issues include better product quality, production increases, low cost and efficient production, emission control, and by-product management and safety. CFX software is a quick and cost-effective way to address these issues. It complements experimental methods, has the ability to stimulate complex physical phenomena, and to investigate novel processes, and the ability to create a virtual lab or virtual prototyping of processes. CFX has been used for a variety of applications in the iron and steel industry: continuous casting, solidification, SEN design, tundish flows, refractory wear, blast furnace modeling. CFX has the capabilities to model the complex phenomena encountered in steel production. For additional information visit AEAT online at www.software.aeat.com/cfx.

Paul Debski of Bricmont, Inc. followed Mr. Guetari. He noted that CFD could achieve a great deal in terms of solving emissions concerns/combustions models. CFD can examine nitrogen oxide emissions. He also noted Bricmont’s interest in electromagnitics.

DEPARTMENT OF ENERGY NATIONAL LABORATORIES CAPABILITIES FOR CFD IN THE STEEL INDUSTRY

Shen-Lin Chang from Argonne National Laboratory (ANL) and Thomas O'Brien from the National Energy Technology Laboratory (NETL) presented DOE National Laboratories capabilities for CFD in the steel industry.

According to Shen-Lin Chang, examples of CFD capabilities at ANL include:

- Flow simulation of fluid catalytic cracking reactors
    - Three-phase flow
    - Complex chemical reactions
- Flow simulation of long pulverized coal pipeline
    - Particle pile-up
- Glass furnace modeling
    - Coupling of combustion space and glass melter
    - Spectral radiation heat transfer
    - Multi-phase flow

Thomas O'Brien, as highlighted by Dr. Thompson, noted the MFCRC vision is to "provide multiphase CFD capabilities to the chemical industry…with the same reliability as single phase CFD." The MFCRC goals include:

- Accurate and efficient numerical methods
- High-fidelity submodels
- Well validated simulations
- In-house industrial applications

He discussed simulation of chemically reactive flows, including O_3 decomposition, SiH_4 pyrolysis, $SiCl_4$ hydrogenation and CH_4 combustion.

UNIVERSITY CAPABILITIES AND APPLICATIONS FOR CFD IN THE STEEL INDUSTRY

Yun Li of Carnegie Mellon University, Yogesh Sahai of The Ohio State University, Chenn Zhou of Purdue University Calumet, and Brian Thomas of the University of Illinois at Urbana-Champaign, presented their institutions' capabilities and applications for CFD in the steel industry.

Yun Li noted future CFD work at Carnegie Mellon University including the desire to complete and polish the current model for post-combustion in the EAF and to extend the model for post-combustion in BOF. Other future work includes development of combustion models for coal/oil/natural gas-oxygen burner/injector used in various metallurgical processes such as EAF, BF and reheat furnaces. For the EAF post-combustion model, future work includes development of a de-post combustion model and optimization of the parameters used in the model. Other future work includes development of a model for air infiltration and possibly including the nitrogen oxide reaction development of a model for scrape pile, and to run the simulation with varying boundary conditions.

Yogesh Sahai followed, noting The Ohio State University's work on the following research topics:

- Melt flow and mixing in gas-stirred ladles

- Temperature change and flow in melt during ladle holding and tapping
- Melt flow, heat transfer, and mixing in continuous casting tundishes
- Melt flow, heat transfer, and solidification in slab casing mold
- Stress analysis in solidifying shell of continuous casting slab
- Melt flow, heat transfer, solidification, and thermo-mechanical stress analysis in thin strip casting
- Melt flow and heat transfer in shot sleeve of die casting
- Post combustion in basic oxygen furnaces
- Bubble formation on wetting and non-wetting substrate

There are various computer codes which are used including self-developed, OSU Code (based on TEACH Code) FIDAP, FLUENT, FLOW3D and a code named SPLASH (Simple Program for Liquid/Air System Hydrodynamics) from Imperial College in England.

Next, Chenn Zhou of Purdue University Calumet gave a presentation on Evaluation of Erosion Patterns in a Blast Furnace Hearth Using a CFD Model, a joint project by Isapt Inland, Inc., ANL, and Purdue University Calumet. Ispat is convinced "…that the use of modern advanced technologies such as CFD provide the most cost-effective solution to gauge the condition of the hearth and understand the reason for changes." The objectives are to develop a state-of-the-art CFD code that can simulate the flow, heat transfer, and erosion patterns in a blast furnace as well as develop a CFD model-based monitor/control strategy for prolonging the campaign life of a blast furnace. The CFD model is expected to provide the blast furnace engineers a powerful tool to:

- Visualize the flow and temperature patterns inside the hearth of furnace
- Understand the impact of changes in the internal conditions in the hearth on wear patterns and the true nature of the on-line measurements
- Assess the state of the hearth to prevent unexpected operation disruptions
- Design a monitoring and controlling system for prolonging campaign life and deferring the need for an extended shutdown for a rebuild.

Brian Thomas described the importance of computational models for further improvements of the continuous casting process. CFD model applications by his group at the University of Illinois include:

- Nozzle design
- Argon gas injection optimization
- Mold flow pattern optimization
- Mold powder/flux optimization
- Grade transition optimization
- Optimal casting speed to avoid shell thinning
- Understanding and control of meniscus phenomena

Brian Thomas concluded that future advances will come from ideas based on an improved understanding of the process. Computational models will grow in importance due to faster computers, better models, and increased difficulty of empirical experiments.

Facilitated Session Results: Applications of CFD in the Steel Industry

Hot Metal Production	BOF/EAF	Refining	Tundish/ Continuous Casting	Reheat Furnace	Downstream Processes
Concentration, filtration, sintering, roasting, smelting, drying Blast furnace burden distribution Blast furnace hearth (flow, heat transfer, erosion patterns) Desulfurization Rotary hearth furnace Iron carbide reactor	Post combustion Off-gases and slag/melt interaction in the EAF BOF hoods (combustion instability)	Ladle stirring Stratification in the ladle Liquid-gas flow interaction Slag entrainment Ladle tapping Vacuum degassing (melt flow, alloy dissolution) Metal-slag interaction during argon rinse	Fluid flow, heat flow, mass transfer, and inclusion motion in the tundish Transient analysis in the tundish Inclusion distribution and deposition in the tundish Argon gas/inclusion interactions Fluid and gas flows in nozzles Flow to the mold; slide gate Heat flow in the mold Impact of gas injection on the mold Fluid flow, heat flow, mass transfer, and inclusion motion in the strand Powder/flux layers Shell Thin strip casting	Combustion modeling Temperature and flow uniformity Temperature of the slab through the furnace	Steel tube cooling Off-gas cleaning (cyclones, electrostatic precipitators) Afterburners Recuperators Dross pickup by the coil in the galvanizing pot Melt flow and heat transfer in die casting Transient analysis during pouring in foundry casting

Meeting Results

- **Key decision: A partnership will be formed**.
  - The meeting participants concluded that there is sufficient interest to further discuss the role of CFD in the steel industry. The participants needed some time to determine how to proceed.

- **List of fundamental CFD steel issues**
  At the meeting, the participants agreed on a list of fundamental CFD steel issues, including the following:
  - Transport of very fine particles across the boundary layer
  - Effect of pressure on gas/solid friction
  - Interaction between solid particle and gaseous phases
  - Gas/metal interactions
  - Turbulence modeling
  - Combustion modeling
  - Vortex flow in draining and continuous flow vessels
  - Free surface flows
  - Gas/liquid regimes in near-injection fields
  - Third bullet (key characteristics and next steps)

- **Steel CFD Partnership key characteristics**
  The Steel CFD Partnership will consist of the following key characteristics:
  - The partnership will likely involve a larger number of partners than the chemical industry CFD partnership, but each partner will likely have a smaller financial commitment than those in the chemical industry
  - The entire partnership group should meet regularly
  - A smaller core working committee should be established that will meet more often than the entire partnership group
  - The group should stay flexible and reevaluate priorities regularly in order to maintain partner interest
  - Some companies may participate in the partnership in order to take advantage of the benefits, even though they themselves do not possess any CFD expertise
  - There is a need to focus on technical barriers to CFD rather than on modeling of specific geometries

- **Next steps**
  - Potential members will evaluate key driving factors and then regroup to discuss the formation of a partnership in more detail to determine
    - What resources will be required from industry and government?
    - What are the underlying fundamental issues?
  - A core working group will be established and will begin laying out the groundwork for the partnership
  - Mark Atkinson of National Steel (matkinson@nationalsteel.com) will contact individuals and collect their comments
  - The core working group will establish a strategy for the partnership
  - Ensure that the revised *Steel Industry Technology Roadmap* contains sufficient input related to CFD
  - Add CFD as an AISI subcommittee topic